

<https://helda.helsinki.fi>

---

## Impacts of timber forwarding on physical properties of forest soils in southern Finland

Toivio, Jenny Helena

2017-12-01

---

Toivio , J H , Helmisaari , H-S M , Palviainen , M M , Lindeman , H , Ala-Ilomäki , J , Sirén , M & Uusitalo , J 2017 , ' Impacts of timber forwarding on physical properties of forest soils in southern Finland ' , Forest Ecology and Management , vol. 405 , pp. 22-30 . <https://doi.org/10.1016/j.foreco.2017.09.022>

---

<http://hdl.handle.net/10138/309148>

<https://doi.org/10.1016/j.foreco.2017.09.022>

---

cc\_by\_nc\_nd

acceptedVersion

---

*Downloaded from Helda, University of Helsinki institutional repository.*

*This is an electronic reprint of the original article.*

*This reprint may differ from the original in pagination and typographic detail.*

*Please cite the original version.*

# 1     **Impacts of timber forwarding on physical properties of forest soils in southern Finland**

2

3     Jenny Toivio<sup>1\*</sup>, Heljä-Sisko Helmisaari<sup>1</sup>, Marjo Palviainen<sup>1</sup>, Harri Lindeman<sup>2</sup>, Jari Ala-Ilomäki<sup>3</sup>, Matti Sirén<sup>3</sup>,  
4     Jori Uusitalo<sup>2</sup>

5     <sup>1</sup>University of Helsinki, Department of Forest Sciences, P.O. Box 27, FI-00014 Helsinki

6     <sup>2</sup>The Natural Resources Institute Finland, Green Technology Unit, Korkeakoulunkatu 7, FI-37200 Tampere

7     <sup>3</sup>The Natural Resources Institute Finland, Green Technology Unit, Koetilantie 5, FI-00790 Helsinki

8     \*Corresponding author: E-mail address: toiviojenny@gmail.com

9

10

## 11     **Abstract**

12     Forest harvesting activities can cause soil damage and disturbance through soil compaction, rut formation and  
13     soil mixing. These affect the soil structure and functions and forest productivity. Soil compaction results for  
14     instance in increased bulk density and decreased porosity, affecting soil moisture, water infiltration and aera-  
15     tion. The effects of timber forwarding on soil physical properties have gained little attention in boreal forests.  
16     These issues will become more important in the future since harvesting operations on unfrozen soils are getting  
17     more common due to the anticipated climate warming.

18     In this study, the changes of forest soil physical properties (bulk density, moisture content and porosity) after  
19     1 to 10 forwarder passes on two fine-grained mineral soil sites in southern Finland were analysed. Penetration  
20     resistance and rut formation were also measured. The measurements were performed in three periods with  
21     different soil moisture conditions. The test drives were carried out with a conventional 8-wheeled forwarder  
22     with total mass of 29.8 tons.

23     Soil bulk density increased and porosity decreased after the machinery passes. However, soil moisture content  
24     increased on one site and mainly decreased on another. The first three passes caused the greatest compaction  
25     and rutting, the first pass having the strongest impact. After the first and third pass 34-55 % and over 70 % of  
26     the total mean rut depth was formed, respectively. Further passes only had slight effects. The compaction and  
27     changes of soil physical properties appeared to be greater in dry conditions. Rut formation and soil mixing

28 were greater in moist conditions. The results are, however, site-specific, and more research is needed to  
29 achieve a better understanding of the relationships between different factors affecting impacts of timber for-  
30 warding on soil.

## 31 **Highlights**

- 32 - Traffic by heavy machinery has significant impacts on soil properties
- 33 - First passes cause the strongest impacts
- 34 - Impacts depend highly on soil characteristics and actual site conditions

## 35 **Keywords**

36 timber harvesting, soil damage, soil compaction, soil protection, rut formation

37

38

## 39 **1. Introduction**

40 Soil is one of the most important components in ecosystems, providing key services such as production of  
41 biomass and energy. It is also a key component of carbon, nutrient and water cycles and gas exchange.  
42 However, soil is usually not an object of specific protection objectives and targets and is rather brought indi-  
43 rectly in connection with activities aimed at the protection of air, water or vegetation (EUA, 2002). In recent  
44 decades, however, soil has gained more importance, social visibility and attention. The European Union pub-  
45 lished in 2016 a report on the implementation of the Soil Thematic Strategy, which was adopted already in  
46 2012 (European Commission, 2016). The United Nations declared 2015 as the International Year of Soils with  
47 the aim to raise awareness on the importance of healthy soil (European Commission, 2014). Sustainable soil  
48 management practices, soil protection and preservation are essential for food security, water quality and plant  
49 production.

50 The concern of tree and soil disturbances through forest operations with bigger, heavier and more powerful  
51 machines has grown in the past decades (e.g. Ala-Ilomäki et al., 2011; Hartanto et al., 2003; Jansson and  
52 Johansson, 1998; Rohand et al., 2004). Forest operations and mechanical stress can result in serious and  
53 prolonged changes in soil, affect soil functions and properties, reduce soil and forest productivity and eventu-

ally cause financial losses (e.g. Elliot et al., 1999; Jansson and Johansson, 1998; Lüscher et al., 2010; Sutherland, 2003). In recent years there has been an increasing interest in sustainable forest management, and a detailed review of the available literature on machinery-induced negative effects on forest soils is provided by Cambi et al. (2015).

Mechanized harvesting and terrain transport have been reported to cause multiple impacts such as soil compaction, rut formation, changes in soil micro climate, stem damage, reduced tree and root growth, increased soil erosion, vulnerability to fungus infections and loss of biodiversity, organic matter, value and volume of trees (e.g. Bygden et al., 2004; Demir et al., 2007; Elliot et al., 1999; Marshall, 2000; Nugent et al., 2003; Sirén et al., 2013). Soil compaction is of high importance because of its effects on soil functions, processes and properties. For instance, it increases the soil bulk density and shear strength, modifies the pore system and soil structure and decreases soil moisture content, porosity, water and air infiltration, respiration and gas exchange (e.g. Bagheri et al., 2012; Jansson and Johansson, 1998; Marx et al., 2013; Nugent et al., 2003; Rohand et al., 2004; Susnjar et al., 2006). In addition, the absorption of nutrients and water by trees and other vegetation are negatively affected in compacted soil (Susnjar et al., 2006; Rohand et al., 2004).

Soil bearing strength is one of the most important characteristics for the quality of ground usability (Susnjar et al., 2006). It indicates the capacity of the soil to resist external forces and affects the trafficability, production efficiency and damages caused by timber haulage (Susnjar et al., 2006). Soil strength and vulnerability to compaction are mainly influenced by its moisture content and particle size distribution (e.g. Lüscher et al., 2010; Marx et al., 2013; Susnjar et al., 2006). Also other factors, such as coarse roots, can increase the bearing capacity of soil. Thus, soils with high moisture content, fine textured soils and peatlands are sensitive to soil damage and compaction (e.g. Marx et al., 2013; Nugent et al., 2003; Sirén et al., 2013; Spoor et al., 2003; Uusitalo and Ala-Illomäki, 2013; Zeleke et al., 2007). The most fertile spruce stands are located on moist and fine-grained soils with a low bearing capacity (Eliasson and Wästerlund, 2007). Also, as spruce horizontal roots are superficial, these stands are especially vulnerable to logging damage (Sirén et al., 2013).

Frozen soil has a better bearing strength, which ensures more efficient harvesting and causes less soil disturbance (Susnjar et al., 2006; Sutherland, 2003). In Finland, up to 60 % of logging is carried out between October and March, when the soil is frozen (Sirén et al., 2013). However, due to the anticipated climate warming and increasingly mild winters a greater proportion of logging needs to be carried out while the soil is not frozen, which may increase the risk for soil disturbances. Whether dry and warm autumn or mild winter with

83 little snow and frost but high soil moisture content would be a more suitable season for Norway spruce thinning  
84 has been brought up by Sirén et al. (2013).

85 The greatest impact of machinery traffic occurs direct in the extraction trails, after the first passes and in the  
86 uppermost soil (0-10 cm) (e.g. Coder, 2007; Elliot et al., 1999; Froehlich and McNabb, 1983; Jakobsen and  
87 Greacen, 1985; Naghdi et al., 2007; Rab, 2004). However, influences in nearby areas and in deeper soil layers,  
88 at more than 80 cm depth, are also reported (e.g. Ampoorter et al., 2007; Jakobsen and Greacen, 1985;  
89 Lüscher et al., 2010; Naghdi et al., 2007). Furthermore, the forwarder has a greater impact and is a greater  
90 threat to soil than the harvester (Kremer and Schardt, 2007; Surakka and Sirén, 2007).

91 The level of soil and root damage depends mostly on the mass and load of vehicles as well as on soil and site  
92 characteristics such as soil type, texture, structure, moisture, content of organic matter and slope. Other af-  
93 fecting factors include machine equipment (tyres, tracks, chains), speed, number of machinery passes, logging  
94 method, timing and planning of activity and skillness of on-site personnel (e.g. Demir et al., 2007; Jansson and  
95 Johansson, 1998; Kremer et al., 2012; Naghdi et al., 2007; Susnjar et al., 2006).

96 Soil is a limited, non-renewable resource as it takes up to thousands of years for one centimeter of soil to form  
97 and once the soil is damaged, it can take years to recover (European Commission, 2015; HBS, 2015). Soil  
98 regeneration is a long process, and it is mainly limited to the top 15 cm (Susnjar et al., 2006). Top soil regen-  
99 eration time after skidding activities differs from 10 to over 30 years, and even up to irreversibility (e.g. Croke  
100 et al., 2001; Froehlich and McNabb, 1983; Lousier, 1990; Rab, 2004). Especially in the deeper soil layers,  
101 influences of compaction are very long-term (Alakukku et al., 2003; Sakai et al., 2008). Maintaining the soil in  
102 a healthy state is essential for ensuring a stable environment for forest flora and fauna (Sutherland, 2003).

103 A great deal of research has been conducted on technological and biological issues of timber harvesting in  
104 Finland, but hardly any of the work done so far concentrates directly on the pedological approach, i.e. the  
105 changes in soil physical properties and the effect of machinery traffic on soil. The aim of this study was to  
106 evaluate the effects of heavy machinery traffic on forest soil on two fine textured sites in southern Finland. Soil  
107 bulk density, moisture content, porosity and grain size distribution were analysed at two soil depths before and  
108 after machinery passes. Rut depth and cone penetration resistance were measured after each pass. The  
109 measurements were performed in three periods with different soil moisture conditions in September, Novem-  
110 ber and December 2015.

111 Our hypotheses were that

- traffic by heavy machinery compacts the soil, which results in increased bulk density and decreased porosity and soil moisture content,
- soil damage, rutting and compaction are greater in moister soil,
- the impacts increase with the number of machine passages,
- the greatest impact to the soil occur after the first passes.

## 2. Materials and methods

### 2.1 Study sites

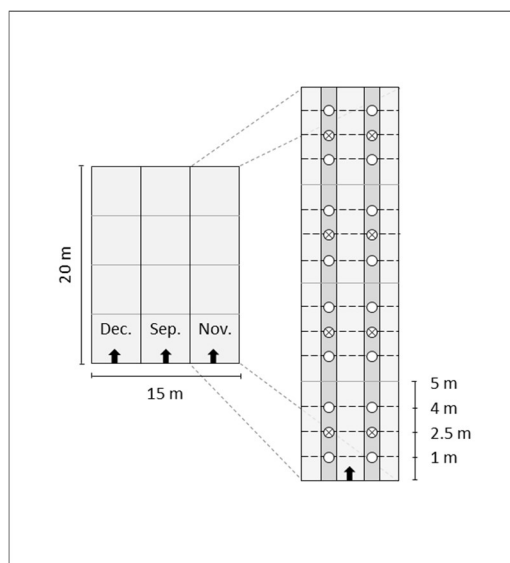
The study sites were located in Vihti in southern Finland and can be classified as the *Oxalis-Myrtillus* forest type (Cajander, 1949). These herb-rich heath forests are relatively fertile sites and comprise approx. 29 % of mineral soils in southern Finland (Hotanen et al., 2008). The mean annual temperature is 4.6°C and the mean monthly temperatures vary between -6°C in January and February and 17°C in July. The mean annual precipitation is 650 mm with clearly more precipitation during the second half of the year (Pirinen et al., 2012).

Site A (Rintelä) (60°24.6 N, 24°23.2 E, around 60 m above sea level) was an even-aged Norway spruce (*Picea abies* (L.) Karst) stand on a silty-clayey soil with a shallow (1-5 cm) humus horizon. The relief was an even slope with minor inclination to northwest. The soil was prepared by ploughing before planting approx. 30 years ago and the ploughing furrows are still visible.

Site B (Pervonmäki) (60°24.4 N, 24°22.4 E, around 70 m above sea level) was a forest of natural origin with different tree species and age classes. The stand was mostly Norway spruce dominated with a mixture of birch (*Betula pendula* Roth) and aspen (*Populus tremula* L.). It was located in a dell and characterised by a silty-sandy soil with a variable thickness (5-20 cm) of organic layer with a shallow peat layer in moist patches. The humus form was moder in both sites.

Five plots of 15 x 20 m were established: three on site A and two on site B. The plots were divided in three test trails (5 x 20 m), one for each study period (Sep., Nov., Dec.) (Fig. 1). Each test trail was further divided into four study sections (5 x 5 m). The lines were carefully marked on the ground in order to keep the measurement points constant. The maximal amount of machinery passes was 10, which was always reached except on site B in November as the bearing capacity collapsed due to high soil moisture content after the third pass.

139 In December the tests were performed only on site A. Detailed description of the number of the measurements  
140 and soil samples is shown in Table 1 and explained in further chapters.



141

142 Figure 1. Schematic maps of a study plot with the three test trails (left) and a test trail with the measurement  
143 points: (o) cone penetration resistance and rut depth measurement points, (x) soil sample points.

144

145 Table 1. Description of the measurements and soil sample collection. \*Due to the wet sandy soil on site B, all  
146 samples of soil depth 10-20 cm could not be collected: 7 samples in September and 3 in November.

Description	Rut depth						Cone penetration resistance						Soil samples					
	Site A			Site B			Site A			Site B			Site A			Site B		
	Sep.	Nov.	Dec.	Sep.	Nov.	Dec.	Sep.	Nov.	Dec.	Sep.	Nov.	Dec.	Sep.	Nov.	Dec.	Sep.	Nov.	Dec.
Measurements on one test trail	24	24	24	24	24	-	24	24	24	24	24	-	8	8	8	8	8	-
Number of plots	3	3	3	2	2	-	3	3	3	2	2	-	3	3	3	2	2	-
Number of passages	10	10	10	10	3	-												
Number of measurements (before and after all passes)							2	2	2	2	1 (only before)	-	2	2	2	2	1 (only before)	-
Number of soil depths													2	2	2	2*	2*	-
Total number of values (n)	720	720	720	480	144	-	144	144	144	96	48	-	96	96	96	57	29	-

147

148 Both sites were clear-cut before the first measurements in September. The harvesting and processing of the  
149 trees were carried out from outside the plots to keep them intact. Harvesting residues were collected and the  
150 test trails were placed in order to avoid travelling over stumps, as this inevitably causes uneven weight distri-  
151 bution and soil loading. This succeeded well on site A as the trees were planted in rows. However, on site B  
152 the forwarder had to travel over several stumps because of the natural origin of the forest.

153 The machinery passes were carried out with an 8-wheeled Ponsse Elk forwarder equipped with Nokia Forest  
154 King F2 710/45-26.5 tires, universal Olofsfors EVO tracks on the rear bogie and Superhokki 160 TS chains on  
155 the rear wheels of the front bogies. The forwarder was further loaded with 9 800 kg of pulpwood. The total  
156 mass was 29 800 kg.

157

## 158 **2.2 Measurement of soil properties**

159 To determine the effects of machinery passes on soil properties, dry soil bulk density (BD), moisture content  
160 (VWC - volumetric water content), total porosity and soil particle size distribution were analysed in laboratory.

161 Soil samples were taken with a core sampler, 500 mm in height and 25 mm in diameter, before and after all  
162 passes and from every predefined measurement point along the test trail (see Fig. 1). In December a round  
163 sampling tube with a diameter of 46 mm was used. Two mineral soil samples were taken at depths of 0-10 cm  
164 and 10-20 cm, in total of 96 samples from site A in each study period (see also Table 1). Sample collection on  
165 site B was more difficult due to the wet sandy soil. During the first period 57 samples were taken and during  
166 the second period 29 samples were taken before the machine traffic. The thickness of the organic layer was  
167 measured in the field.

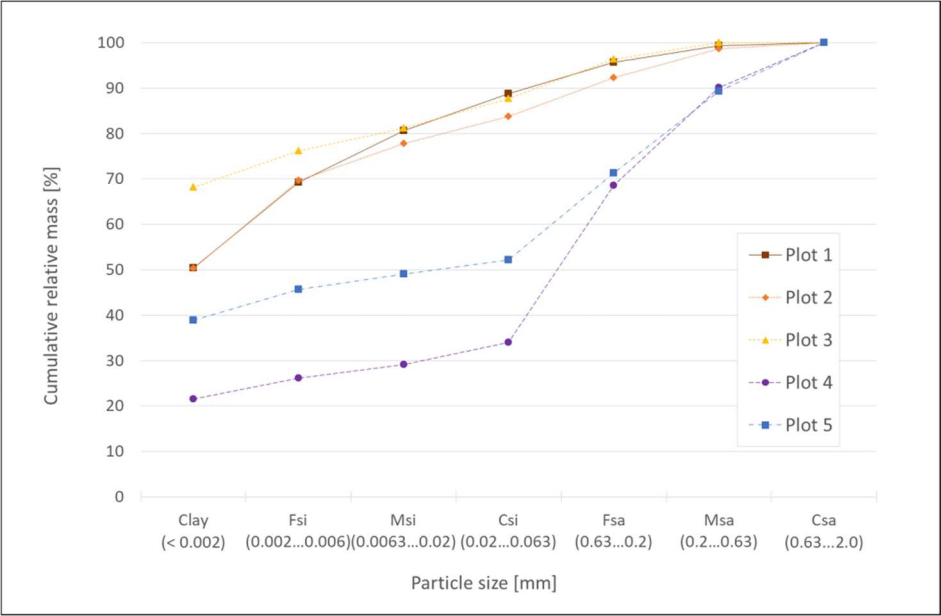
168 The VWC was calculated from the difference between the wet and oven-dry soil mass (60°C, 3-6 days). Soil  
169 BD was calculated by dividing the oven-dry soil mass by the wet volume of the sample. Porosity ( $\phi$ ) was  
170 calculated from BD and density of soil solids (DS) using the formula  $\phi = ((DS-BD)/DS)*100$ , where a DS value  
171 of 2.65 g/cm<sup>3</sup> for mineral matter and a mean value of 1.4 g/cm<sup>3</sup> for organic matter were used (Hillel, 1982).  
172 To estimate the soil particle size distribution, common methods sieving and sedimentation were used  
173 (Heiskanen and Tamminen, 1992).

174 Additionally, three soil profiles were characterized for estimating the soil type and site conditions. Soil samples  
175 were taken from A-, B- and C-horizons and the parameters soil particle size distribution, organic matter content,  
176 colour and pH were analysed.

177 Soil particle size distributions of the test samples can be regarded as silty clay on site A (plots 1-3), whereas  
178 it varies between sandy and clay loam on site B (plots 4-5). The distribution for each plot is the mean result  
179 from both test depths, which were very similar. The grain size was coarser on site B and there was more  
180 variation in grain size and thickness of the soil horizons and the humus layer (Fig. 2). Considering the soil



181 physical properties, fine ( $< 0,06$  mm) and coarse ( $> 0,06$  mm) particle sizes are often distinguished, as many  
 182 of the properties change at this particle size (Heiskanen, 2003). The mean soil particle size shows that the  
 183 soils on site A and in plot 5 can be defined as fine grained and in plot 4 as coarse grained mineral soils.  
 184 According to the World Reference Base for Soils (2006) the soils can be categorized as a haplic Gleysol dystic  
 185 (site A) and a histic Gleysol dystic (site B).



186  
 187 Figure 2. Soil particle size distribution on each plot (site A: plot1-3, site B: plot 4-5).

188  
 189 **2.3 Monitoring of penetration resistance and rut formation**

190 Cone penetration resistance (CPR) was measured with the Eijkelkamp Penetrologger 0615SA penetrometer  
 191 consisting of an 80 cm long rod and a 60-degree cone with a diameter of 11.28 mm (1 cm<sup>2</sup>). Depth readings  
 192 were captured every 1 cm by an ultrasonic depth sensor. The results were further analysed and means calcu-  
 193 lated to describe the strength and compaction of the soil. Penetration resistance was measured on both wheel  
 194 ruts before and after all passes (see also Table 1), but also after every pass in two study sections on each site  
 195 to define the impact of single passes. As in soil sample collection, measurements were made only before the  
 196 passes on site B in November as no further measurements were possible and reasonable due to the deep rut  
 197 formation and soil disturbance.

198 To measure rut formation a self-levelling construction laser device, a levelling rod and a laser beam detector  
 199 were used. Before the test drives, a reference height was marked on a tree and a reference height level of the  
 200 ground was measured for every measurement point to be located on wheel ruts. After each pass the height of

the rut bottom was determined using the laser beam detector and the levelling rod (see also Table 1). Afterwards the rut depth was calculated by comparing the rut bottom height to the reference height of each measurement point. Furthermore, means of rut depth for each section, plot and site were calculated.

## **2.4 Statistical analyses**

A general linear model (GLM) was used to study the relationship of soil bulk density, moisture content and porosity to the treatment (machine passes) and other fixed factors and their interactions. Treatment, site, month (September, November and December) and soil depth (humus, 0-10 cm and 10-20 cm mineral soil) and their interactions were defined as fixed factors in the model. The differences in soil bulk density, moisture content and porosity before and after all machinery passes in each measurement point were tested with paired-samples t-tests. Differences were considered statistically significant when  $P$  was  $< 0.05$ . A linear regression analysis was used to examine the relationship between rut depth, soil bulk density, cone penetration resistance and soil moisture content. Statistical tests were performed using IBM SPSS version 23 (IBM Corp, Armonk, NY, USA).

## **3. Results**

### **3.1 Soil properties**

Site, month and soil depth significantly affected the soil moisture content (Table 2). It increased from September to November about 10 % on each site, but only slightly from November to December (Fig. 3). On site A the VWC was 21-31 % in September, 33-45 % in November and 40-48 % in December. Site B was moister having 30-40 % VWC in September and 42-49 % in November. The deeper soil sample depth (10-20 cm) was about 5 % moister on site A. Site B had an organic layer up to 20 cm with higher VWC (up to 58 % in Nov.) and therefore, the VWC was more variable. Soil BD and porosity were significantly affected by treatment, site, month and soil depth (Table 2). The dry soil bulk density was higher and consequently porosity lower in December and at 10-20 cm depth. Before the test drives, BD ranged overall between 0.8-1.3 g/cm<sup>3</sup> on site A and 1.1-1.6 g/cm<sup>3</sup> on site B and porosities between 50-70 % and 40-55 % respectively.

227 There was a significant interaction between treatment and month and between treatment and depth (Table  
228 2), indicating that the machinery passes had different effect on soil BD, porosity and moisture content in dif-  
229 ferent months and at different depths. Greater effects and changes occurred in dry September and at the 0-  
230 10 cm depth than in moister November and December and at the 10-20 cm depth. Notable changes in humus  
231 layer properties were found on site B. As expected, BD increased and porosity generally decreased through  
232 machinery passes. However, contrasting results can be observed for the VWC: increases on site A and de-  
233 creases on site B.

234 There was a significant interaction between site and treatment (Table 2) and the changes in soil properties  
235 were statistically significant on site A (Fig. 3). After the machinery passes, BD increased by 45 % at 0-10 cm  
236 depth and by 34 % at 10-20 cm depth in September. The VWC increased around 28 % and porosity decreased  
237 22 % at both depths. In November BD increased by 32 % at 0-10 cm depth and by 7 % at 10-20 cm depth.  
238 The corresponding values in December were 17 % and 4 %, respectively. The VWC increased almost 20 %  
239 at 0-10 cm depth, but remained rather unchanged at 10-20 cm depth during both last periods. Porosity was 16  
240 % and 6 % lower in November and 11 % and 4 % lower in December after the test driving.

241 The results between the plots on site A were similar, but the results for the two plots on site B were mostly  
242 opposite and will therefore not be discussed further as mean values. There were significant changes only for  
243 the humus measurements and VWC in plot 5. These significant results have the same trend as for site A with  
244 the exception of VWC in plot 5. In plot 4, BD increased by 31 % at the upper depth and by 13 % at the lower  
245 depth, whereas in plot 5 it decreased 18 % and 11 %, respectively. Consequently, porosity decreased around  
246 20 % in plot 4 and increased about 17 % in plot 5 at both depths. The VWC decreased at the upper depth  
247 around 20 % in both plots, but at the lower depth after all passes it was 7 % lower in plot 4 and 15 % higher in  
248 plot 5.

249 Table 2. The relationship of soil moisture content, bulk density and porosity to the machinery passes (treat-  
250 ment) and other fixed factors and their interactions in a general linear model (GLM).

	Moisture content			Bulk density			Porosity		
	Degrees of freedom	F-value	Significance, p-value	Degrees of freedom	F-value	Significance, p-value	Degrees of freedom	F-value	Significance, p-value
Intercept	1	14294.07	< 0.001	1	13006.12	< 0.001	1	17888.35	< 0.001
Site	1	11.17	0.001	1	72.91	< 0.001	1	59.02	< 0.001
Treatment	1	1.36	0.244	1	97.55	< 0.001	1	141.84	< 0.001
Month	2	238.59	< 0.001	2	13.66	< 0.001	2	11.06	< 0.001
Depth	2	27.56	< 0.001	2	317.88	< 0.001	2	95.19	< 0.001
Site * Treatment	1	39.55	< 0.001	1	33.82	< 0.001	1	27.37	< 0.001
Site * Depth	1	8.46	0.004	1	2.07	0.151	1	1.68	0.196
Treatment * Month	2	4.23	0.015	2	14.95	< 0.001	2	12.1	< 0.001
Treatment * Depth	2	7.46	0.001	2	12.3	< 0.001	2	34.81	< 0.001
Month * Depth	2	0.22	0.8	2	0.71	0.493	2	0.57	0.564
Site * Treatment * Depth	1	5.5	0.02	1	0.02	0.903	1	0.01	0.913
Site * Month * Depth	2	3.26	0.04	2	2.02	0.134	2	1.64	0.196

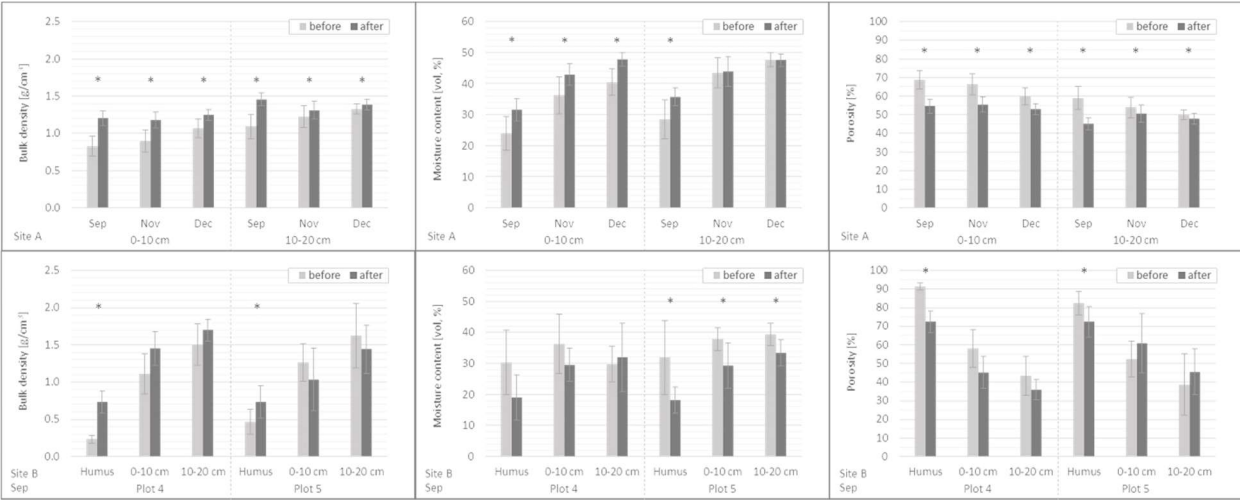


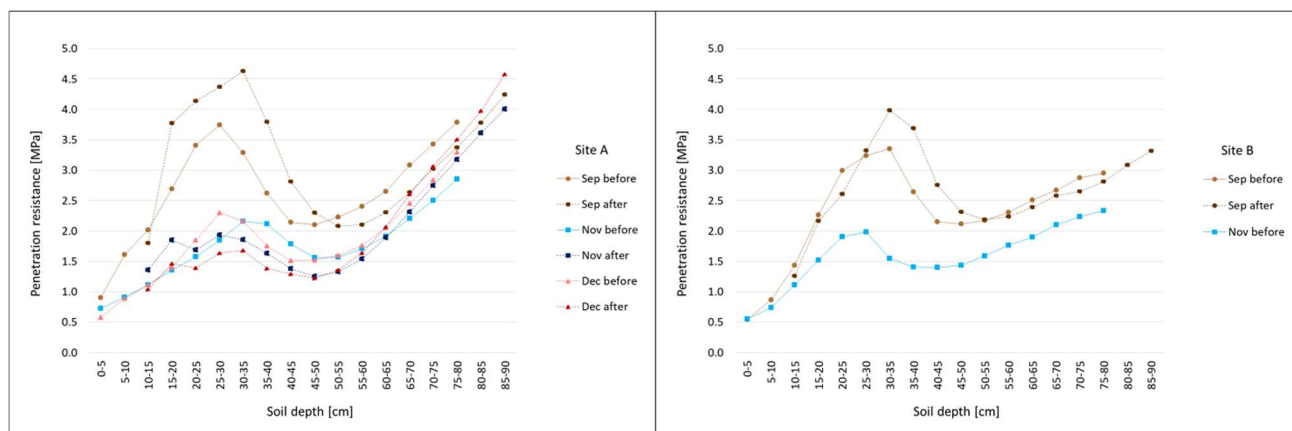
Figure 3. Soil bulk density, moisture content and porosity measurements before and after all machinery passes on site A (all test periods) and site B (September). \* $P < 0.05$ .

### 3.2 Penetration resistance and rut formation

The CPR measurements had higher values and greater compaction in dry September than in moister November and December (Fig. 4). Penetration resistance and soil compaction were thus clearly lower in moist conditions. The greatest changes occurred in the top 60 cm soil depth. In September, CPR was 0.5-1.5 MPa higher in the first 40-50 cm soil depth on site A and between 30-50 cm soil depth on site B after the machinery passes. In contrast, the results for November and December showed decreased values after passing. The overall level of CPR was, however, clearly lower than in September. The first three passes had the greatest

264 impact on the top soil of about 30 cm, whereas the further passes caused compaction at greater depths,  
 265 especially in moist conditions (not shown).

266



267 Figure 4. Mean penetration resistance before and after the test drive on site A and B. Measurements after  
 268 the test drives are represented with a correction of 10 cm according to the approx. mean rut depth.

269

270 In contrast to CPR, rut formation followed a clear pattern in moist conditions (Fig. 5, Table 3). In the silty clay  
 271 soil on site A there were minor differences between the study periods, while in the sandy clay loam soil on site  
 272 B deep ruts were formed in November. The mean rut depth after all passes on site A was 9 cm in September  
 273 and approx. 13 cm in November and December, rutting being only less than 1 cm greater in December. On  
 274 the other hand, VWC had a strong influence on rutting on site B. In September, the mean rut depth was 12  
 275 cm, but in November the bearing capacity of the soil collapsed after the initial passes, the mean rut depth  
 276 being nearly 25 cm after only three passes.

277 Rut depth increased almost linearly after each test drive. The greatest rutting and strongest effect occurred  
 278 after the first machinery passes, whereas the further passes had a minor impact. On site A the rut depth of  
 279 approx. 4.5 cm (all periods) and on site B 6.5 cm (September) and 9 cm (November) was measured after the  
 280 first pass. The following passes increased the rut depth by 1-2 cm, but after the fourth pass in September and  
 281 the sixth pass in November and December the increase was less than 1 cm. However, in moist conditions the  
 282 further passes caused more rutting. The mean final rut depth in September on site A was exceeded after 5-7  
 283 passes in November and December. On site B in November each pass caused rutting of 7-9 cm. Except for  
 284 the test on site B in November, 34-55 % of the total mean rut depth was formed after the first pass, 47-66 %  
 285 after the second and 72-86 % after the fifth pass (Table 3).

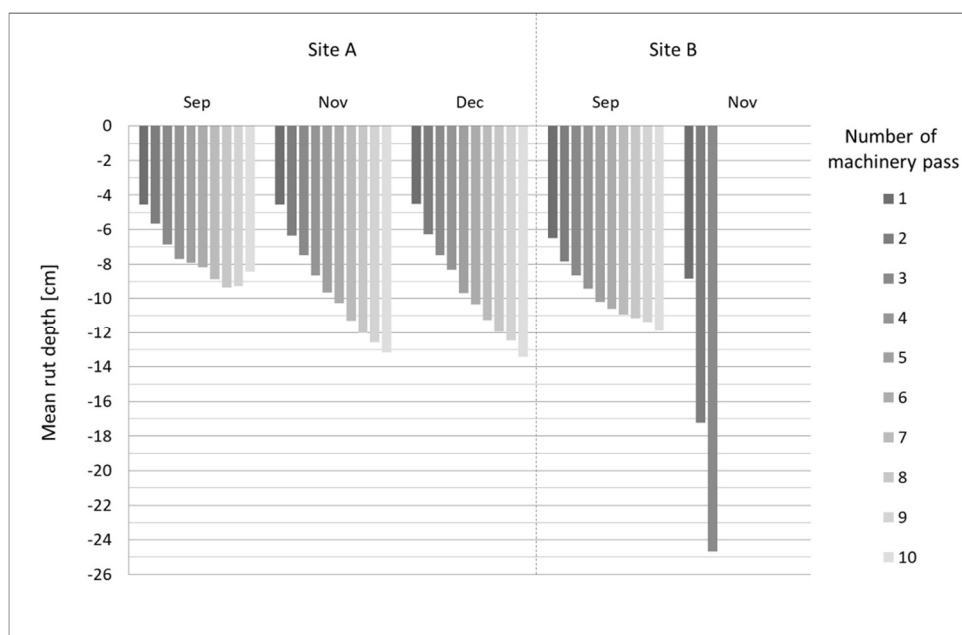


Figure 5. Rut depths after each test drive on both sites.

Table 3. Rut depth values.

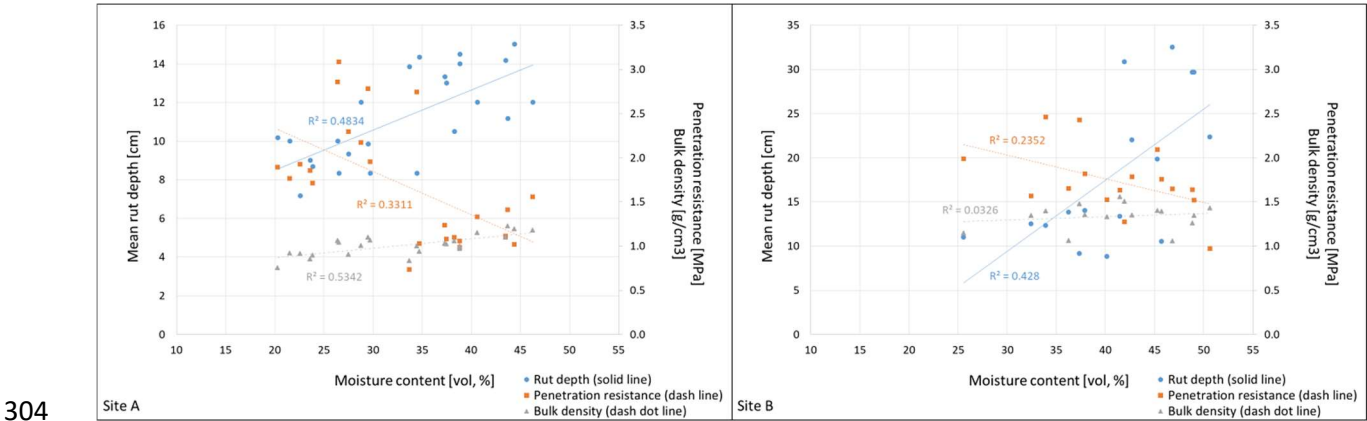
Number of passages	Mean rut depth [%]				
	Site A			Site B	
	Sep	Nov	Dec	Sep	Nov
1	49	35	34	55	36
2	61	48	47	66	70
3	74	57	56	73	100
4	86	73	72	86	
5	96	86	84	92	
Mean final rut depth (cm)	9.2	13.1	13.4	11.9	24.7
Range of rut depth (cm)	4-14	3-18	8-18	0-21	0-38

### 3.3 Statistical analysis

Linear regression analyses were estimated between the variables BD, VWC and CPR measured before the passing in September and November. The mean rut depth after passes was also analysed against VWC before the passes. All measurements were calculated and compared with the corresponding soil sample depths of 0-10 cm and 10-20 cm.

Correlations among the parameters were stronger on site A than on site B (Fig. 6). VWC had a strong positive correlation with BD (53 %), whereas with CPR the correlation was negative and rather moderate (33 %). On

299 site B, VWC did not correlate with BD (3 %) and only moderately with CPR (24 %). The relationship between  
 300 BD and CPR was 53 % on site A and 14 % on site B (not shown).  
 301 However, VWC explained 48 % on site A and 43 % on site B of the variation in rut depth. Thus, increased soil  
 302 moisture content caused deeper and increased rutting. This could also be well observed on site B, where deep  
 303 ruts formed and a lot of soil mixing occurred in November (Fig. 7).



305 Figure 6. Relationships between bulk density, penetration resistance, rut depth and moisture content on site  
 306 A and B (September).



308 Figure 7. Test trails after the machinery passes in September and November on both sites.

#### 311 4. Discussion

312 We found that BD generally increased after trafficking, which is consistent with previous observations (e.g.  
 313 Froehlich and McNabb, 1984; Klaes et al., 2016; Naghdi et al., 2016). However, the traffic-induced increase in  
 314 BD was lower in moist conditions. Similar results were observed for the CPR measurements: the CPR values

315 increased in dry conditions, whereas also decreased values were measured in moist conditions. Some re-  
316 searchers, e.g. Braunack (1986), Lenhard (1986) and Jakobsen and Greacen (1985) also reported on de-  
317 creased CPR and BD values after trafficking. This phenomenon might be due to the higher organic material  
318 content of samples from trafficked soil as the organic matter mixes into the mineral soil through trafficking  
319 (Jansson and Johansson, 1998; Lenhard, 1986). An alternative explanation can be the loss of thixotropic  
320 strength in soil or the increase in soil moisture content to near saturation, which would have rendered the soil  
321 non-compactable (Jakobsen and Greacen, 1985). However, the decreases are presumed to be temporary.  
322 Jansson and Johansson (1998) found that repeated measurements 14 months after trafficking showed a sta-  
323 tistically significant increase in CPR in trafficked plots compared with untrafficked control areas. Furthermore,  
324 the measured correlation between BD and CPR on site A corresponds to the 50-60 % correlation as stated for  
325 all soils by Coder (2007).

326 The porosity measurement was calculated from the BD and therefore the results are related. Porosity generally  
327 decreased due to the trafficking, with the same exceptions as in BD. Decrease of soil porosity is a common  
328 effect following machinery passing as found in many studies, e.g. Bagheri et al. (2012), Demir et al. (2007),  
329 Jakobsen and Greacen (1985), Jansson and Johansson (1998), Susnjar et al. (2006).

330 The effect of machinery passes on hydrological soil properties are dependent on site characteristics. In this  
331 study the VWC showed increased (site A) and decreased (site B) values after trafficking. A decrease of VWC  
332 has been commonly reported (e.g. Demir et al., 2007; Susnjar et al., 2006), but also increased values have  
333 been measured as the result of passing (e.g. Klaes et al., 2016; Eliasson and Wästerlund, 2007). Huang et al.  
334 (1996) found both effects on hydraulic properties. Wronski and Murphy (1994) reported that an increase in the  
335 water content could be possible due to trafficking on some sub-plastic clay soils. However, machinery passing  
336 causes structural changes in the soil, which leads to a decrease in soil water potential and reduction in air  
337 permeability (Wronski and Murphy, 1994).

338 According to the common recommendations for forestry practice, a rut depth of 10 cm is permitted (Lüscher  
339 et al., 2010; MMM, 2014; Äijälä et al., 2014). In Finland it has been further specified with the maximum pro-  
340 portion of deep ruts (>10 cm) being 4 % of the total length of strip roads (MMM, 2014; Äijälä et al., 2014). The  
341 limit of 10 cm rut depth was reached at the latest after five passes on each site and period, except on site A in  
342 September. As in many other reported studies, the initial (1-3) passes caused the greatest rutting (e.g. Jakob-  
343 sen and Greacen, 1985; Klaes et al., 2016; Naghdi et al., 2016; Susnjar et al., 2006).



344 Lüscher et al. (2010) classified strip roads in three categories according to the soil damage after trafficking.  
345 Type 1 shows a slight, elastic impact on soil and ruts of under 10 cm, but largely undamaged soil. Type 2 has  
346 a greater impact with plastic deformation, low rut side formations and deeper ruts, which are however mostly  
347 under 10 cm. In this case the soil damage is not yet severe. In type 3 trafficking causes the formation of deep  
348 ruts (> 10 cm) and high rut side formations as well as compaction and serious damage into the top and sub  
349 soil. Therefore, the soil suffers from long-term damage and is also ecologically negatively affected (Meyer et  
350 al., 2011). From a soil protection perspective, this demonstrates a loss and alteration of soil functions, proper-  
351 ties and structures, which is a clear evidence on soil damage and a violation of the principles of sustainability  
352 (Kremer et al., 2012).

353 The test tracks in the present study can be categorised in various manners, depending on the site and the  
354 trafficking month. September tracks on site A can be classified into type 1 and November and December into  
355 type 2. On site B trafficking caused a greater impact (see Fig. 7). In September, it was classified into type 2,  
356 while in November the damage corresponded clearly type 3. Even though VWC on site A in December was  
357 close to VWC values of site B in November, soil bearing capacity was not exceeded. Based on this, we con-  
358 clude that it is very relevant and important to evaluate different factors and site characteristics while estimating  
359 effects of harvesting operations.

360 It has been well established that a thawed fine-grained soil with high VWC results in low bearing capacity,  
361 while similar soil in frozen condition has a high bearing capacity (Shoop, 1993; Susnjar et al., 2006). This is  
362 also one reason why harvesting operations are traditionally carried out in the winter time on frozen soils with  
363 a snow cover protecting the ground from direct contact. Trafficking on wet soils should be avoided as soil  
364 disturbance and rut formation are greater than in dry conditions. When all soil pores are filled with water, the  
365 soil is saturated. Near the saturation point, the cohesive forces break and the soil loses its bearing capacity.  
366 This point was reached on site B in November, when VWC was near 50 %. Consequently, the bearing capacity  
367 was very low, and deep ruts were formed. According to Miller and Sirois (1986) all moderately deep soils with  
368 finer than a sandy loam with clay subsoil (as on site B) have a very high potential for rutting und compaction  
369 and are generally the most severely disturbed in logging in wet conditions. However, only slight differences  
370 between the test periods were found on site A (see also Fig. 7). Even though VWC was high, the bearing  
371 capacity was not exceeded as on site B. This might be due to soil type and site characteristics. It can thus be  
372 concluded that the effects of trafficking are highly site-specific and depend on actual site and weather condi-  
373 tions.

374 Through optimised prevention, economical, biological and pedological losses, high costs of aftercare as well  
375 as soil and tree damages and disturbances can be avoided. Depending on site characteristics and timing,  
376 different methods can be applied. Recommendations for best practices to limit soil damage have been well  
377 summarized by Cambi et al. (2015). For example, protective harvesting methods e.g. slash cover and rein-  
378 forcements have been widely recommended to reduce the direct impact of machinery passes (e.g. Eliasson  
379 and Wästerlund, 2007; McDonald and Seixas, 1997; Sirén et al., 2013). Furthermore, careful planning, timing,  
380 professionalism, high level of expertise and care taken by the on-site personnel are very important (e.g. Edlund,  
381 2012; Kremer et al., 2012; Sutherland, 2003). Additionally, models and prediction methods are being devel-  
382 oped to predict and lower the risk for soil and tree damages, and to help the planning of forest activities. For  
383 example, Zeleke et al. (2007) have established a Pressure-Sinkage-model for prediction of potential site dam-  
384 age by timber harvesting and extraction machinery traffic. In the Natural Resources Institute Finland, a model  
385 is being developed, which aims to forecast the soil bearing capacity and rutting risk based on various environ-  
386 mental factors and actual weather conditions. The increasing digitalisation and development of remote sensing  
387 methods also bring many alternatives and benefits, especially for the planning of forest activities.

388 Finally, we conclude that soil damage and rut formation were greater in moister soil as expected, whereas  
389 CPR results showed greater compaction in dry conditions. The impacts also increased with the number of  
390 machine passages, though the greatest impact to the soil occurred after the first passes as hypothesized. The  
391 results for increased bulk densities and decreased porosities were significant. However, the results for the  
392 changes in moisture content do not completely confirm our hypothesis as decreased and increased values  
393 were measured.

394

## 395 **5. Conclusions**

396 Harvesting and heavy machinery operations are connected with negative influences on soil. These should be  
397 considered in a wider context, since the damages from harvesting operations cannot be completely avoided.  
398 Nevertheless, these should be minimized where possible.

399 The results of this study show clear impacts and changes in the measured parameters due to the forest ma-  
400 chinery passing. However, the effects vary depending on the site conditions and the soil properties such as  
401 soil type and moisture content. The soil damage can be described mainly as not severe on site A, whereas

402 severe damage occurred on site B with VWC near saturation. According to the laboratory analysis, the ma-  
403 chinery passing caused a minor impact on BD, VWC and porosity in moist conditions. The CPR measurements  
404 showed greater soil compaction in dry soil conditions, whereas deeper ruts formed in moist conditions. The  
405 impact of machinery passing was greater on top soil and after the first three passes.

406 Based on our results, we suggest that research for defining critical limits on the pedological and biological  
407 aspects of harvesting is needed for a better understanding of the environmental interactions and relationships.  
408 As concluded by Schoenholtz et al. (2000), for the assessment of sustainability in forestry activities, knowledge  
409 of forest soil properties has to be extended in order to predict the dynamic behaviour of soil processes and the  
410 effects of management practices on these processes. Through increasing information of machinery-induced  
411 effects on forest soils, more detailed management strategies, practical guidelines and vulnerability classifica-  
412 tion could be provided as there are for arable lands (e.g. Alakukku et al., 2003; Chamen et al., 2003; Spoor et  
413 al., 2003). More comprehensive studies in different locations and conditions need to be carried out. Further  
414 development of research methods and soil and tree protective harvesting are also necessary.

415

## 416 **Acknowledgements**

417 This study is based on an M.Sc. thesis of the corresponding author. The driving tests were done under the  
418 research project "Enhancing timber harvesting on sensitive sites", carried out at the Natural Resources Institute  
419 Finland. The authors are grateful to Marjut Wallner at the University of Helsinki, Department of Forest Sciences  
420 for guidance in the laboratory analyses and to the laboratory staff of the Natural Resources Institute Finland  
421 for particle size analysis. We also thank Metsä Group and the personnel of Metsäkoneurakointi Pekka Liiri Oy  
422 for their cooperation. The support by Maj and Tor Nessling foundation is gratefully acknowledged.

423

424

## 425 **References**

426 Ala-Ilomäki J., Högnäs, T., Lamminen, S., Sirén, M., 2011. Equipping a Conventional Wheeled forwarder for  
427 peatland operations. *Int. J. For. Eng.* 22 (1), 7-13.

428 Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tjink, F.G.J., van der Linden, J.P., Pires, S., Sommer, C.,  
429 Spoor, G., 2003. Prevention strategies for field traffic-induced subsoil compaction: a review. Part 1. Ma-  
430 chine/soil interactions. *Soil Till. Res.* 73, 145-160.

431 Ampoorter, E., Goris, R., Cornelis, W.M., Verheyen, K., 2007. Impact of mechanized logging on compaction  
432 status of sandy forest soils. *For. Ecol. Manage.* 241, 162-174.

433 Bagheri, I., Kalburi, S.B., Akef, M., Khormali, F., 2012. Effect of Compaction on Physical and Micromorpho-  
434 logical Properties of Forest Soils. *Am. J. Plant Sci.* 3, 159-163.

435 Braunack, M.V., 1986. Changes in physical properties of two dry soils during tracked vehicle passage. *J.*  
436 *Terramech.* 23 (3-4), 141-151.

437 Bygden, G., Eliasson, L., Wästerlund, I., 2004. Rut depth, soil compaction and rolling resistance when using  
438 bogie tracks. *J. Terramech.* 40, 179-190.

439 Cajander, A.K., 1949. Forest types and their significance. *Acta For. Fenn.* 56, 72 pp.

440 Cambi, M., Certini, G., Neri, F., Marchi, E., 2015. The impact of heavy traffic on forest soils: A review. *For.*  
441 *Ecol. Manage.* 338, 124-138.

442 Chamen, T., Alakukku, L., Pires, S., Sommer, C., Spoor, G., Tjink, F., Weisskopf, P., 2003. Prevention strat-  
443 egies for field traffic-induced subsoil compaction: a review. Part 2. Equipment and field practices. *Soil Till.*  
444 *Res.* 73, 161-174.

445 Coder, K.D., 2007. Soil Compaction Stress & Trees: Symptoms, Measures, Treatments. University of Geor-  
446 gia. Warnell School Outreach Monograph WSFNR07-9.

447 Croke, J., Hairsine, P., Fogarty, P., 2001. Soil recovery from track construction and harvesting changes in  
448 surface infiltration, erosion and delivery rates with time. *For. Ecol. Manage.* 143, 3-12.

449 Demir, M., Makineci, E., Yilmaz, E., 2007. Investigation of timber harvesting impacts on herbaceous cover,  
450 forest floor and surface soil properties on skid road in an oak (*Quercus petrea* L.) stand. *Build. Environ.* 42,  
451 1194-1199.

452 Edlund, J., 2012. Harvesting in the Boreal Forest on Soft Ground – Ways to reduce ground damage. Licen-  
453 tiate thesis at the University of Agricultural Sciences. Umeå.

454 Eliasson, L., Wästerlund, I., 2007. Effects of slash reinforcement of strip roads on rutting and soil compaction  
455 on a moist fine-grained soil. *For. Ecol. Manage.* 252, 118-123.

456 Elliot, W. J., Page-Dumroese, D., Robichaud, P.R., 1999. The Effects of Forest Management on Erosion and  
 457 Soil Productivity. [http://forest.moscowsl.wsu.edu/smp/docs/docs/Elliot\\_1-57444-100-0.html](http://forest.moscowsl.wsu.edu/smp/docs/docs/Elliot_1-57444-100-0.html) (accessed  
 458 20.10.2015).

459 EUA (= Europäische Umweltagentur), 2002. Auf dem Boden der Tatsachen: Bodendegradation und nachhal-  
 460 tige Entwicklung in Europa. Umweltthemen-Serie 16. (in German).

461 European Commission, 2014. International Year of Soils 2015. A/RES/68/232.

462 European Commission, 2015. Soil. [http://ec.europa.eu/environment/soil/index\\_en.htm](http://ec.europa.eu/environment/soil/index_en.htm) (accessed  
 463 31.07.2015).

464 European Commission, 2016. Soil. [http://ec.europa.eu/environment/soil/three\\_en.htm](http://ec.europa.eu/environment/soil/three_en.htm) (accessed  
 465 17.08.2017).

466 Froehlich, H. A., McNabb, D. H., 1983. Minimizing soil compaction in Pacific Northwest forests, in: Stone,  
 467 E.L. (Eds.), Forest soils and treatment impacts. Proceedings of the Sixth North American Forest Soils Con-  
 468 ference, University of Tennessee, Knoxville, pp. 159-192.

469 Hartanto, H., Prabhu, R., Widayat, A.S.E., Asdak, C., 2003. Factors affecting runoff and soil erosion: plot-  
 470 level soil loss monitoring for assessing sustainability of forest management. For. Ecol. Manage. 180, 361-  
 471 374.

472 HBS (= Heinrich-Böll-Stiftung, Institute for Advanced Sustainability Studies, Bund für Umwelt- und Natur-  
 473 schutz Deutschland & Le Monde Diplomatie), 2015. Bodenatlas 2015. [http://www.boell.de/sites/de-  
 474 fault/files/bodenatlas2015.pdf](http://www.boell.de/sites/default/files/bodenatlas2015.pdf) (accessed 31.07.2015).

475 Heiskanen, J., 2003. Maaperän ominaisuudet, in: Mälikönen, E. (Ed.), Metsämaa ja sen hoito, pp. 39-62. (in  
 476 Finnish).

477 Heiskanen, J., Tamminen, P., 1992. Maan fysikaalisten ominaisuuksien määrittäminen. Metsäntutkimuslai-  
 478 toksen tiedonantoja 424. (in Finnish).

479 Hillel, D., 1982. Introduction to soil physics. Academic press.

480 Hotanen, J.-P., Nousiainen, H., Mäkipää, R., Reinikainen, A., Tonteri, T., 2008. Metsätyypit – opas kasvu-  
 481 paikkojen luokitteluun. Hämeenlinna (Metsäkustannus Oy). (in Finnish).

482 Huang, J., Lacey, S.T., Ryan, P.J., 1996. Impact of forest harvesting on the hydraulic properties of surface  
 483 soil. Soil Sci. 161 (2), 79-86.

484 Jakobsen, B.F., Greacen, E.L., 1985. Compaction of sandy forest soils by forwarder operations. Soil Till.  
 485 Res. 5, 55-70.

486 Jansson, K.-J., Johansson, J., 1998. Soil changes after traffic with a tracked and a wheeled forest machine:  
 487 a case study on a silt loam in Sweden. *Forestry* 71 (1), 57-66.

488 Klaes, B., Struck, J., Schneider, R., Schüller, G., 2016. Middle-term effects after timber harvesting with heavy  
 489 machinery on a fine-textured forest soil. *Eur. J. For. Res.* 135, 1083-1095.

490 Kremer, J., Schardt, M., 2007. Vergleich der Bogiebänder Eco-Track und Eco-Baltic mit dem Reifen, in: Bay-  
 491 erische Landesanstalt für Wald und Forstwirtschaft: Neue Wege beim Bodenschutz. *Waldforschung aktuell*  
 492 59, 3-5. (in German).

493 Kremer, J., Wolf, B., Matthies, D., Borchert, H., 2012. Bodenschutz beim Forstmaschineneinsatz. Merkblatt  
 494 der Bayerischen Landesanstalt für Wald und Forstwirtschaft 22. (in German).

495 Lenhard, R.J., 1986. Changes in Void Distribution and Volume During Compaction of a Forest Soil. *Soil Sci.*  
 496 *Soc. Am. J.* 50 (2), 462-464.

497 Lousier, J.D., 1990. Impacts of forest harvesting and regeneration on forest sites. *Land Manage. Rep.* 67.

498 Lüscher, P., Frutig, F., Sciacca, S., Spjevak, S., Thees, O., 2010. Physikalischer Bodenschutz im Wald.  
 499 Merkblatt für die Praxis 45. Birmensdorf (Eldg. Forschungsanstalt WSL). (in German).

500 Marshall, V.G., 2000. Impacts of forest harvesting on biological processes in northern forest soils. *For. Ecol.*  
 501 *Manage.* 133, 43-60.

502 Marx, B., Randel, A.C., Schilli, C., Hoeborn, G., Helmus, M., Rinklebe, J., 2013. Ressourcenschutzpotenzial  
 503 bei Baumaßnahmen bezüglich Boden. Endbericht des Forschungsprogramms „Zukunft Bau“ des Bundes-  
 504 ministeriums für Verkehr, Bau und Stadtentwicklung. (in German).

505 McDonald, T. P., Seixas, F., 1997. Effect of slash on forwarder soil compaction. *J. For. Eng.* 8 (2), 15-26.

506 Meyer, C., Lüscher, P., Schulin, R., 2011. Verdichteten Boden mit Schwarzerlen regenerieren? *Wald und*  
 507 *Holz* 10, 40-43. (in German).

508 Miller, J.H., Sirois, D.L., 1986. Soil Disturbance by Skyline Yarding vs. Skidding in a Loamy Hill Forest. *Soil*  
 509 *Sci. Soc. Am. J.* 50 (6), 1579-1583.

510 MMM (= Maa- ja metsätalousministeriö), 2014. Valtioneuvoston asetus metsien kestävästä hoidosta ja käy-  
 511 töstä. (in Finnish).

512 Naghdi, R., Bagheri, I., Akef, M., Mahdavi, A., 2007. Soil compaction caused by 450C Timber Jack wheeled  
 513 skidder (Shefarood forest, northern Iran). *J. For. Sci.* 53 (7), 314-319.

514 Naghdi R., Solgi, A., Ilstedt, U., 2016. Soil chemical and physical properties after skidding by rubber-tired  
 515 skidder in Hyrcanian forest, Iran. *Geoderma* 265, 12-18.

516 Nugent, C., Kanali, C., Owende, P.M.O., Nieuwenhuis, M., Ward, S., 2003. Characteristic site disturbance  
 517 due to harvesting and extraction machinery traffic on sensitive forest sites with peat soils. *For. Ecol. Ma-*  
 518 *nage.* 180, 85-98.

519 Pirinen, P., Simola, H., Aalto, J., Kaukoranta, J.-P., Karlsson, P., Ruuhela, R., 2012. Tilastoja Suomen ilmas-  
 520 tosta 1981-2010. Helsinki (Ilmatieteen laitos). (in Finnish).

521 Rab, M.A., 2004. Recovery of soil physical properties from compaction and soil profile disturbance caused  
 522 by logging of native forest in Victorian Central Highlands, Australia. *For. Ecol. Manage.* 191, 329-340.

523 Rohand, K., Al Kalb, A., Herbauts, J., Verbrugge, J.-C., 2004. Changes in some mechanical properties of a  
 524 loamy soil under the influence of mechanized forest exploitation in a beech forest of central Belgium. *J.*  
 525 *Terramech.* 40, 235-253.

526 Sakai, H., Nordfjell, T., Suadicani, K., Talbot, B., Bøllehuus, E., 2008. Soil compaction on forest soils from  
 527 different kinds of tires and tracks and possibility of accurate estimate. *Croatian J. For. Eng.* 29 (1), 15-27.

528 Schoenholz, S.H., Van Miergroet, H., Burger, J.A., 2000. A review of chemical and physical properties as  
 529 indicators of forest soil quality: challenges and opportunities. *For. Ecol. Manage.* 138, 335-356.

530 Shoop, S.A., 1993. Thawing soil strength measurements for predicting vehicle performance. *J. Terramech.*  
 531 30 (6), 405-418.

532 Sirén M., Ala-Ilomäki, J., Mäkinen, H., Lamminen, S., Mikkola, T., 2013. Harvesting damage caused by thin-  
 533 ning of Norway spruce in unfrozen soil. *Int. J. For. Eng.* 24 (1), 60-75.

534 Spoor, G., Tijink, F.G.J., Weisskopf, P., 2003. Subsoil compaction: risk, avoidance, identification and allevia-  
 535 tion. *Soil Till. Res.* 73, 175-182.

536 Surakka, H., Sirén, M., 2007. Poimintahakkuiden puunkorjuun nykytietämys ja tutkimustarpeet. *Metsätieteen*  
 537 *aikakauskirja* 4, 373-390. (in Finnish).

538 Susnjar M., Horvat, D., Seselj, J., 2006. Soil compaction in timber skidding in winter conditions. *Croatian J.*  
 539 *For. Eng.* 27 (1), 3-15.

540 Sutherland, B.J., 2003. Preventing soil compaction and rutting in the boreal forest of western Canada. A  
 541 practical guide to operating timber-harvesting equipment. *For. Eng. Res. Inst. Can. Advantage Vol.* 4 (7).

542 Uusitalo, J., Ala-Ilomäki, J., 2013. The significance of above-ground biomass, moisture content and mechan-  
 543 ical properties of peat layer on the bearing capacity of ditched pine bogs. *Silva Fenn.* 47 (3), 1-18.

544 WRB (=World Reference Base for Soil Resources) (2006): A Framework for International Classification, Cor-  
 545 relation and Communication: World Soil Resources Reports. 103. (Food and Agriculture Organization).

546 Wronski, E. B. & G. Murphy (1994): Responses of Forest Crops to Soil Compaction, in: Soane, B.D., Van  
547 Ouwerkerk, C., (Eds.), Soil Compaction in Crop Production. Developments in Agricultural Engineering 11,  
548 317-342. Amsterdam (Elsevier).

549 Zeleke, G., Owende, P.M.O., Kanali C.L., Ward, S.M., 2007. Predicting the pressure-sinkage characteristics  
550 of two forest sites in Ireland using in situ soil mechanical properties. Biosyst. Eng. 97, 267-281.

551 Äijälä, O., Koistinen, A., Sved, J., Vanhatalo, K., Väisänen P., 2014. Metsänhoidon suositukset. Metsätalou-  
552 den kehittämiskeskus Tapion julkaisuja. (in Finnish).